RECENT ADVANCES IN THE PREDICTION OF TRACKED VEHICLE SEISMIC SIGNATURES

September 1999

Anthony G. Galaitsis and William B. Coney
BBN Technologies
A Part of GTE
70 Fawcett Street, Cambridge MA 02138

ABSTRACT

Under this program, sponsored by the National Ground Intelligence Center (NGIC), BBN Technologies continued the development of a model for the prediction of the seismic signatures of foreign tracked vehicles initiated during an earlier phase [1]. The signatures are estimated by combining the ground excitation forces predicted by the tracked vehicle dynamics model TRAXION [1-4] with the propagation transfer functions obtained from a Rayleigh wave model [1,5].

Earlier results [1] suggested that different tracked vehicles display significantly different and potentially exploitable seismic signature characteristics. Those results were valid over a limited range of operating conditions because of various modeling assumptions. The current system includes additional and more realistic features in the model, such as a dual track and an uneven ground profile, to extend its capabilities and validity over a broader range of conditions. Furthermore, we have also implemented specialized graphics resources to facilitate the display and interpretation of the predicted results.

While an extensive parametric study is still pending, simulations performed to date with the upgraded model a) generally, support the earlier predictions [1], and b) suggest that there are additional signature features that may exploited during vehicle operation over uneven ground.

1.0 INTRODUCTION

Background: Seismic signature information is a valuable resource in the detection and classification of tracked vehicles because it can be acquired covertly, utilizing passive sensor to collect signals often transmitted along Non-Line-of-Sight (NLOS) paths. As a result, under the previous phase of this multi-phase NGIC-sponsored program, BBN Technologies (BBN) initiated a systematic development of a tracked vehicle seismic signature prediction model to explore signature characteristics that may be exploited in such identification and classification. Both phases of this work leveraged the resources of earlier efforts [2-4] that had focused on modeling US-made tracked vehicles.

Objective: The ultimate objective of the current program is the development of a seismic model for the simulation of foreign tracked vehicles of interest to NGIC. The previous phase of the program produced the general framework for the desired model, and completed several of the resources or tools required to populate this framework.

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY) 01-09-1999	**2. REPORT TYPE**	**3. DATES COVERED (FROM - TO)** xx-xx-1999 to xx-xx-1999
4. TITLE AND SUBTITLE Recent Advances in the Predictionof Tracked Vehicle Seismic Signatures Unclassified		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Galaitsis, Anthony G. ; Coney, William B. ;		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME AND ADDRESS BBN Technologies 70 Fawcett Street Cambridge , MA 02138		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS ,		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT A PUBLIC RELEASE ,		

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Under this program, sponsored by the National Ground Intelligence Center (NGIC), BBN Technologies continued the development of a model for the prediction of the seismic signatures of foreign tracked vehicles initiated during an earlier phase [1]. The signatures are estimated by combining the ground excitation forces predicted by the tracked vehicle dynamics model TRAXION [1-4] with the propagation transfer functions obtained from a Rayleigh wave model [1,5].

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				13	Fenster, Lynn lfenster@dtic.mil
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	Public Release		19b. TELEPHONE NUMBER International Area Code Area Code Telephone Number 703 767-9007 DSN 427-9007

The primary objective of the current phase was to continue the development of the resources required to improve the utility and reliability of the seismic noise model. This objective was achieved through the completion of the following milestones:

- development of the dual track model
- development of an uneven ground profile model
- adaptation of specialized graphics resources, and
- identification of additional areas in need of future attention

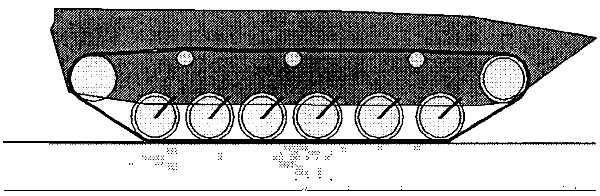
These milestones also represent significant steps towards achieving the ultimate objective of this multi-phase program.

2.0 TECHNICAL APPROACH

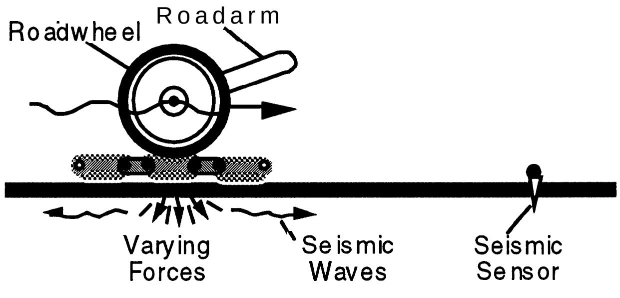
This section focuses primarily on the description of modeling capabilities that were developed and implemented into computer code during this phase of the program. It also contains a brief and qualitative overview of the tracked vehicle seismic signature model for the purpose of continuity. However, it contains no substantial details on modeling capabilities developed during earlier phases of the program. Readers interested in such details should review References l-4.

Overview: The basic approach, vehicle features, and physical processes involved in the tracked vehicle seismic signature prediction model are illustrated in Figure 1. Figure la is a side view of a representative vehicle that highlights the major components that are accounted for in the model. These include the track, roadwheels, roadarms, drive-sprocket wheel (located at the front or rear, depending on vehicle), idler wheel, and support rollers. Additional suspension components, not depicted in Figure 1, include torsion bars and dampers that Provide a compliant support for the hull and minimize shock and vibration during vehicle operation over irregular terrain.

Adjacent track components (track shoes and connectors) are linked through rubber coated rods ("pins") and they are of the single-pin or double-pin type [3-4]. Most vehicles have wheels with solid rubber tires and many vehicles have also rubber pads on the inner and outer surfaces of the track shoes (Figure 1b).



(a)



(b)

Figure 1. Elements of Tracked Vehicle Seismic Force Prediction. a) Major Vehicle Components, b) Seismic Wave Generation

The translational and rotational behavior of each component in a 2-dimensional space is governed by a differential equation, and its particular response is controlled by its specific inertial, damping and stiffness parameters. The entire vehicle is a many-body system described by a set of coupled nonlinear differential equations that are solved numerically [2-3]. The solution includes time histories of each component's motion and of loads between all coupled

Physically, the track-induced seismic forces arise from the discrete nature of the track; the track's periodic impedance results in a vertical excitation of the roadwheel/track system and, in turn, in a vertical excitation (seismic forcing) of the supporting ground (Figure 1b).

New Features: Past work focused on the description of a single-track system operating over a rigid flat ground to keep the problem complexity at a manageable level. The new capabilities developed and implemented during this phase include a dual track, an uneven ground profile (also capable of modeling discrete bumps), and a set of graphics tools for the display of the predicted results.

Dual track: Figure 2 illustrates the general features of the dual track model. At any given time, a number of track shoes on each side of the vehicle are in direct contact with the ground. However, most of the static load (vehicle weight) as well as the major dynamic loads are applied through the shoes that are directly under the roadwheels. The dynamic loads are partially transmitted through the shoes to the ground and generate seismic waves that propagate away from the vehicle. Since the vehicle is moving, it follows that the seismic source is not only spatially distributed but also in constant motion.

The seismic noise at a sensor location is the superposition of the contributions of wave trains arriving from all excitation areas. Each contribution is a function of its source strength and of the transfer function associated with the corresponding transmission path. These wavetrains are emitted at different times and from different locations, and propagate through different paths (Figure 2), therefore; their contributions interfere constructively or destructively depending on the orientation, distance and speed of the vehicle.

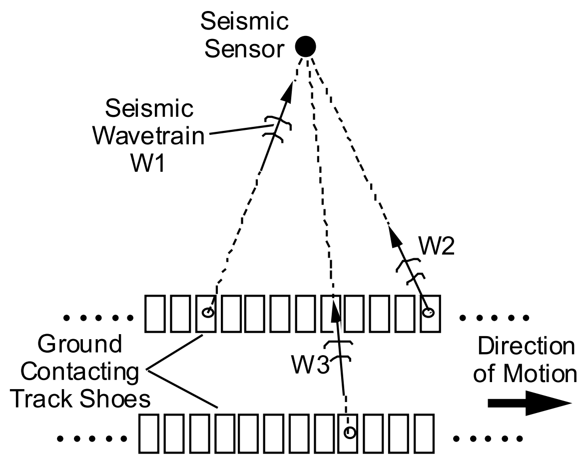


Figure 2. Seismic Wave Contributions from a Distributed Source.

The seismic forces generated by the individual track shoes are predicted by the track dynamics model TRAXION [2], and the track shoe-to-sensor transfer functions are predicted using the Rayleigh wave model [5]. Mathematically, the dual track sources are represented by a time-space dependent force matrix, the transmission paths by a time-space dependent transfer function (or impulse response) matrix, and the seismic noise at the specified sensor location is obtained from the convolution of the source and path matrices. Seismic signatures predicted with the dual track model are presented and discussed in Section 3.

Uneven Ground Profile Model: Earlier versions of TRAXION were based on a flat ground profile (Figure 3a) which was defined by a rigid plane located at a height of y=0. This assumption did not obscure the track-shoe passage effects that are caused by the periodicity of the track impedance. However, it prevented large-scale motions of the suspension system (normally occurring over uneven ground) and, therefore, de-emphasized seismic signature features associated with the suspension response.

The current TRAXION version accounts for an uneven ground profile (Figure 3b), including isolated and pronounced bumps (Figure 3c). Both can be used for better representations of actual terrain profiles, therefore, they increase the realism of the model predictions. The new model approximates actual terrain shapes by a piece-wise linear polygonal curve (Figure 3d). The ground-to-shoe interaction force, **F3**, is proportional to the "overlap area" of the shoe and ground profile, and it is applied at the centroid of the overlap area [2]. The seismic force (shoe-to-ground force) is **-F3**, as dictated by the action-reaction principle.

When the shoe is totally above a single segment (Figure 3d; case S3), the force calculation is similar to that of the earlier model [2] after accounting for the line segment slope which is, generally, different than horizontal. When the shoe overlaps with more than one segment, the force calculation becomes more complex. Two samples, from a large set of shoe/ground contact cases, are also shown in Figure 3d, one with a shoe over a “local peak” (Case S1), and another with a shoe over a “local valley” (Case S2). In the former case, the total shoe/ground force **F1** is calculated from the area of a single and simply-connected region of overlap; in the latter case, the total shoe/ground force is the superposition of the forces **F2** and **F2'** that are calculated from the areas of two disconnected overlap regions.

The uneven ground profile model was used to describe an isolated ground bump in Section 3 in order to explore the effects of such a feature on the seismic signatures of four foreign vehicles.

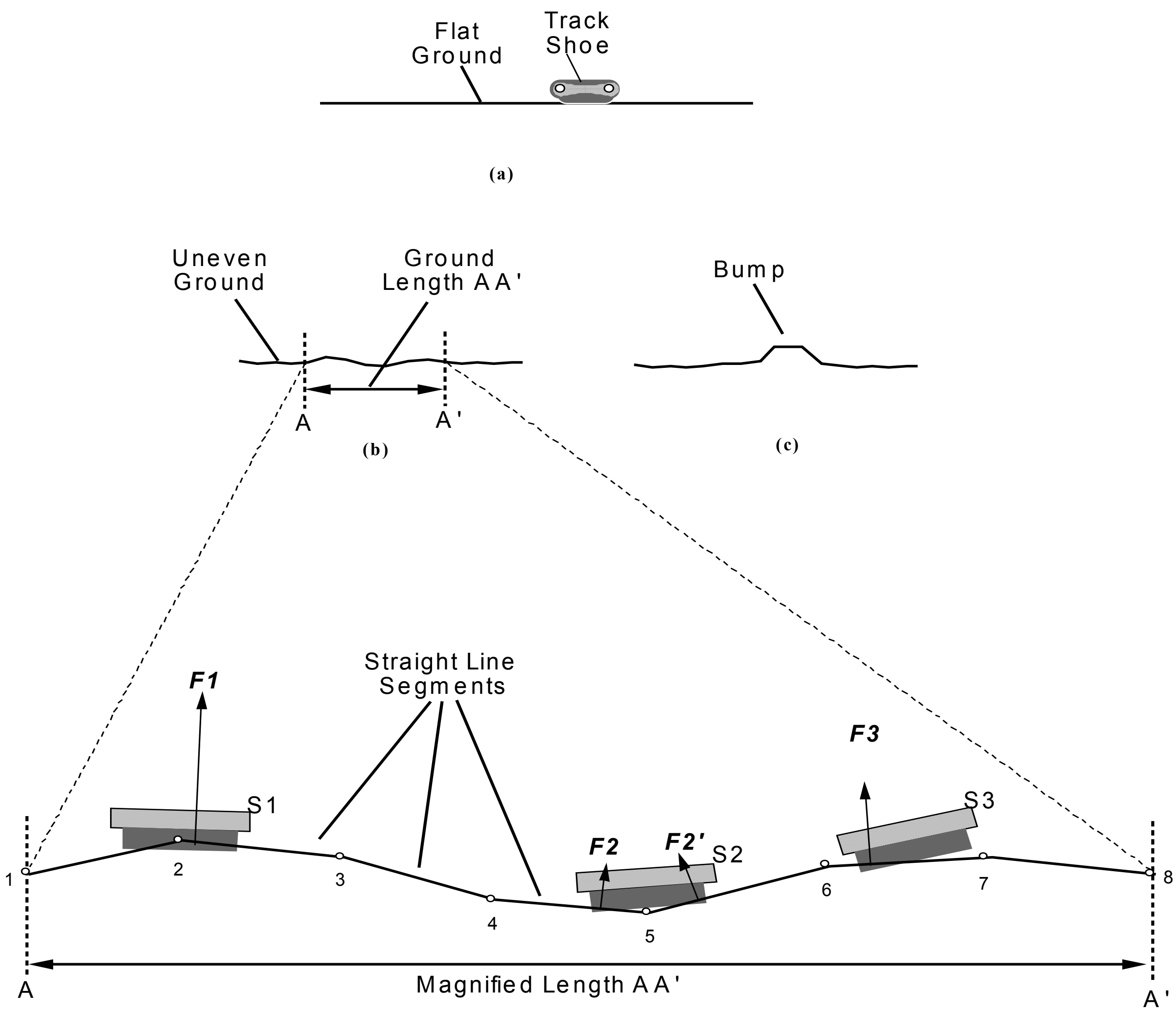


Figure 3. Track/Ground Interaction Features. a) Flat Ground, b) Uneven Ground, c) Discrete Bump d) Track Interaction with Piece-Wise Linear Uneven Ground.

Enhanced Graphics: Each simulation of a single vehicle generates a massive amount of information (time histories or spectra) related to the component response, component loads, seismic forces and seismic signatures. In both phases of the program, some effort was also allocated to the development or adaptation of graphics resources for an efficient display of selected portions of this information in order to facilitate the computer code debugging and the review and interpretation of the predicted results. These resources include:

- Vehicle sideview animations to confirm that the simulations are free of computational artifacts that have been observed in some extreme cases
- Time history displays of dynamic quantities (acceleration, loads, seismic noise, etc.)
- Spectra and spectrogram display of such dynamic quantities

The utility and value of some of these resources can be appreciated during the presentation of the predicted seismic noise results discussed in Section 3.

3.0 SIMULATION RESULTS

The upgraded model outlined in the previous section was applied to foreign tracked vehicles to continue the study initiated in Reference 1 for the identification of seismic signature features that are unique to each vehicle, as well as, of phenomena that may impede such a process.

Simulations were carried out for the Russian-made BMP-2 Mechanized Infantry Combat Vehicle, T-72 Main Battle Tank, MT-LB Armored Utility Vehicle, and ZSU-23-4 Quad 23 mm Self-Propelled Anti-Aircraft Gun System, using the vehicle dynamic parameters that were identified in Reference 1. Seismic signatures were predicted for representative soil parameters and for vehicles operated at constant 35 Kph speed over flat ground or over ground containing a bump.

It should be noted that, despite the recent upgrades, the current model still includes some simplifying assumptions. These include approximations in a) the vehicle model, such as a vertically and torsionally constrained motion of the vehicle's hull Center-of-Gravity, b) the propagation model, such as soil representation by a semi-infinite elastic medium, and, c) specific vehicle and soil dynamic parameters. Accordingly, the predicted seismic signatures presented herein and the associated conclusions should be considered preliminary, pending a rigorous model validation.

Flat Ground Consistency Check: The first few simulations after the integration of the upgraded model ensured that its predictions were consistent with the results of the earlier model in limiting cases where both versions were expected to produce identical results. This was accomplished by predicting the seismic signatures (with both models) for vehicle operation over flat rigid ground.

In the old model, the ground was defined by a rigid plane located at a height of y=0 and extending between $\pm\infty$. Furthermore, seismic signatures were predicted for a single track, i.e., by including only one side of the vehicle. In the present model, the ground is represented by a set of piecewise linear segments of different lengths. Although the new model includes both vehicle sides, a few runs were performed by considering only one side to replicate the old model conditions.

The seismic signature time histories and spectra (similar to those shown in Figure 4c and 4d) from both models were identical, therefore, the consistency check was successful. All simulations, discussed in the remaining of this section, were conducted with the dual track model that includes the effects from both sides of the vehicle.

Operation over Flat Ground - Dual Track: Typical results of a dual-track vehicle model for flat ground operation are shown in Figure 4 along with information about the simulated test site layout.

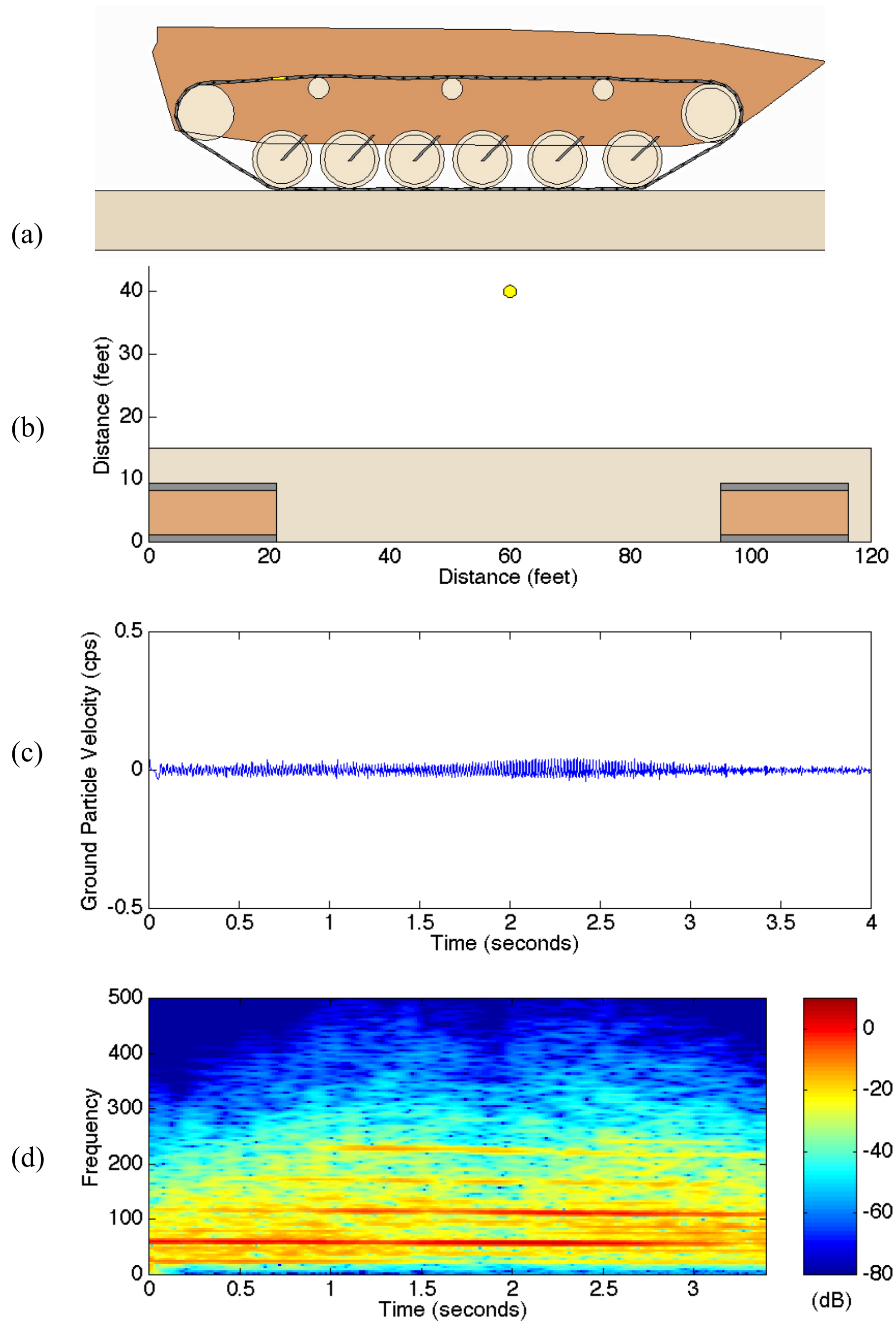


Figure 4. Predicted seismic signature for a BMP-2 operated on flat ground. a) BMP-2 over Flat Ground, b) Plan View of Vehicle Path and Sensor, c) Signature Time History, d) Signature Spectrogram

Figure 4a shows a side view of the modeled vehicle, in this case, a Russian-made BMP-2 Mechanized Infantry Combat Vehicle. As indicated by the sketch, the BMP-2 has six non-uniformly spaced roadwheels, and three idler rollers supporting the upper part of the track strand. Additional significant features, not visible in the illustration, include a forward placed drive-sprocket, a double-pin track, and a torsion bar suspension.

Figure 4b illustrates the test site layout used for the simulation. The vehicle is assumed to move from left to right, with a forward speed of 35 Kph, past a single seismic sensor located 33 ft away from the left side of the vehicle. The seismic signature is analyzed over sequential time segments during the pass-by. The two rectangles above the time axis of Figure 4b, which are separated by a ~112 ft distance, mark the vehicle positions that correspond to the start points of the first and last data analysis windows.

Figure 4c contains the time history of the predicted seismic signature. The first 3.5 sec of the displayed time record corresponds to the 112-yd distance traversed by the vehicle. As expected, the signature level is low when the vehicle is at the left end of the picture, attains its maximum value near the closest point of approach (CPA), and goes down again as the vehicle recedes to the right, away from the sensor. Not surprisingly, the maximum seismic signal occurs <u>after</u> CPA because of the time delay associated with the wave propagation from the vehicle to the sensor.

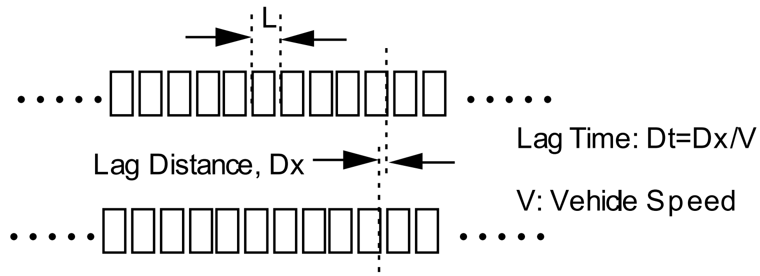
Figure 4d is a spectrogram of the 3.5-sec time history of Figure 4c, displayed in a logarithmic scale (dB). Its distinct horizontal lines represent tones that are associated either with the track shoe passage frequency and its harmonics, or with normal mode frequencies attributable mainly to the suspension system. The characteristics of the track shoe passage tones are closely related to track parameters (track shoe length, weight, etc.), which vary significantly from one vehicle to another, and their frequency is proportional to the vehicle speed. Normal mode tones are determined from the dynamic (inertial, stiffness, and damping) parameters of the suspension system and are speed-independent. Figure 4d shows that both the magnitude and shape of the instantaneous signature spectrum (vertical strips of the spectrogram) vary with time.

The level change is attributable mainly to the variation of the vehicle-to-sensor distance during the simulation time window. The spectrum shape variation (directivity pattern), like the dropouts at certain frequencies near CPA, arises from the interference of waves arriving from different ground contacting track shoes. However, despite these variations, the dominant spectral features, such as the first few tones, maintain their general character throughout the simulation period. The specific features and behavior of these tones are expected to facilitate vehicle classification, especially when fused with information about other types of signatures from the same vehicle.

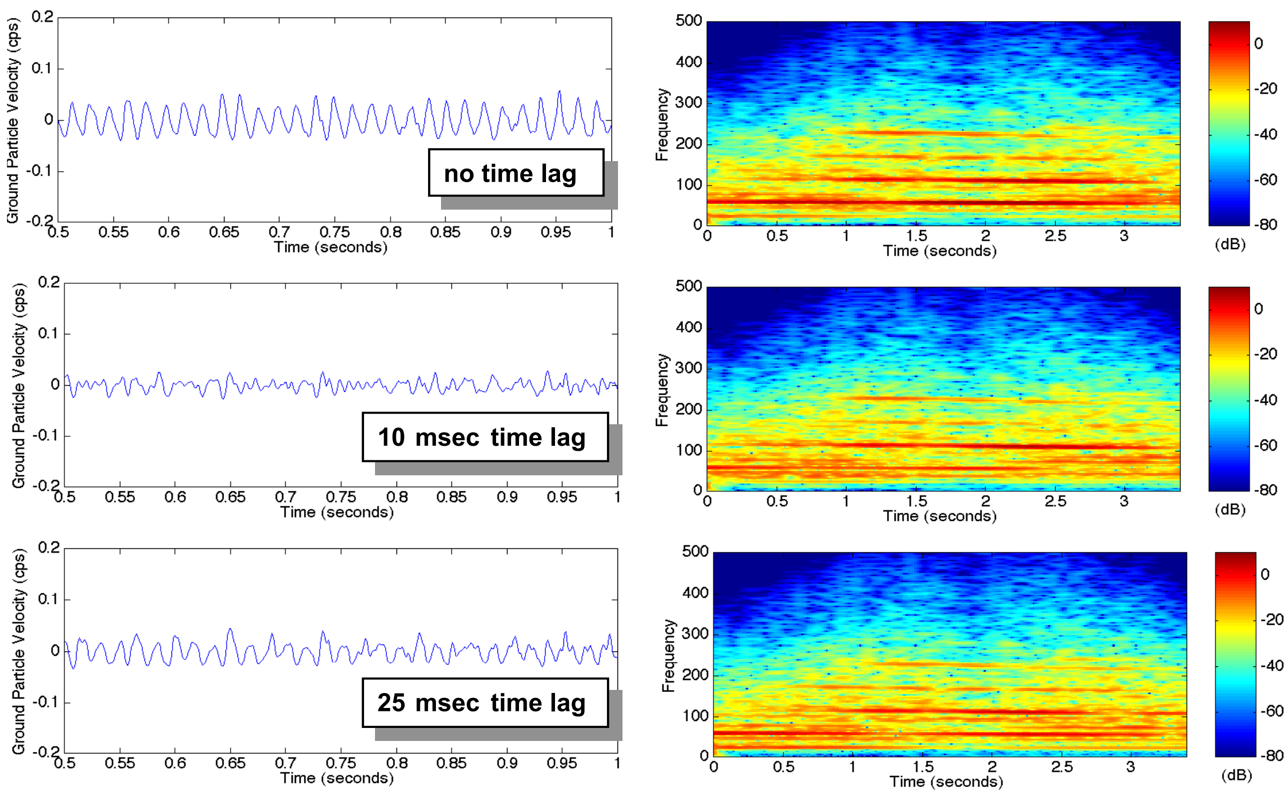
<u>Time Lag between Vehicle Sides:</u> The Figure 4 results were derived under the assumption that the left and right tracks were symmetric about the vehicle centerline. This is rarely the case, however, because these tracks are misaligned every time the vehicle goes even through a slight turn. As a result, there is usually some lag distance, Dx, between the two tracks (Figure 5a) in the fore-aft direction, which corresponds to a lag time Dt=Dx/V, (V: vehicle speed), between the seismic forces generated under the left and right sides of the vehicle. The lag time is an additional parameter of the distributed seismic source that may affect its directivity pattern.

The sensitivity of the directivity pattern to the lag time Dt was explored by performing simulations for several lag times. Representative results are presented in Figure 5b. The three time traces (left side of Figure 5b) show that lag times of 0, 10 msec, and 25 msec can cause the predicted <u>peak</u> seismic signature to change by a factor of 2. The corresponding spectrograms exhibit noticeable variations in the directivity pattern. For example, the track-shoe passage frequency is quite strong near the 1-sec location of the intensity of these tones, and their directivity (tone variation with time or aspect angle) are some of the significantly different features of these vehicles. lag_time=0 spectrogram, but it is partially faded (has a reduced intensity) near the 1-sec location of the lag_time=10 msec spectrogram.

Even though the lag time affects the details of individual spectra, it does not alter the overall character of the corresponding spectrograms in any substantial way. In fact, the effect of the track lag time on the directivity pattern is comparable to the effect of vehicle aspect angle, which is partially responsible for the temporal variation of the Figure 4d spectrogram but does not obscure significantly its major characteristics. In both cases, the first few dominant tones maintain their general character over most of the simulation period, therefore, they are expected to retain their value for the vehicle classification process.



(a)



(b)

Figure 5. Effect of Time Lag Between Tracks on the Predicted Seismic Signature of a BMP-2 Operated on Flat Ground.

Operation over a Bump: The predicted seismic signature of a vehicle riding over an isolated bump is presented in Figure 6. Since the vehicle hull is constrained to move along a horizontal plane, the simulation generates no information about the gross vertical motion of the hull. However, it provides detailed information about the substantial motion of the suspension components, including track, roadwheels, roadarms and torsion bars.

Figure 6a shows side views of the modeled vehicle, again a BMP-2, and the relative size of the 24-in long by 3-in high simulated rigid ground bump. The bump surface is described by a piece-wise linear curve using the newly developed model for uneven ground profile.

In the test site layout of Figure 6b, the vehicle is assumed to move from left to right, with a forward speed of 35 Kph, past a single seismic sensor located 33 ft away off the left side of the vehicle. The vehicle renditions (rectangular shapes) at the left and right ends of the figure, correspond to the time starts of the first and last data analysis windows of the run. During the simulation, the vehicle traverses a ~112 yd length of flat ground containing the single bump indicated by the thick vertical line near the 37-ft location along the horizontal axis.

Figure 6c shows a 4-sec long segment of the predicted seismic signature at the specified sensor location. As expected, the encounter of the vehicle with the bump is marked by a distinct amplitude burst in the predicted time history. The increased intensity (significantly higher than the flat ground CPA amplitudes of Figure 4c) persists throughout the track/bump contact, and "rings" back to a lower level as the suspension motion decays to its flat ground behavior.

Not surprisingly, the left portion of the Figure 6d and Figure 4d spectrograms are identical because they both correspond to vehicle operation over flat ground. The same is true for the extreme right portion of the spectrogram, where the effects of the bump have disappeared. However, there are striking differences after the vehicle encounters the bump. The first difference is the amplitude increase, which is as significant and prominent in the Figure 6d spectrogram as in the Figure 6c time history. The second difference is the presence of additional spectral lines that are equally dominant as the track-shoe passage frequency lines. For example, Figure 6d has two more prominent lines in the vicinity of 2.2-2.3 sec not present in Figure 4d. These lines are believed to originate in the response of the suspension components such as the roadwheels, roadarms, and torsion bars. Over flat ground, the motion of these components is small, therefore, the corresponding tones are insignificant compared to the track-shoe passage tones. However, a vehicle interaction with a sizeable bump amplifies the motion of these components, intensifies the corresponding vehicle/ground forces, and produces additional seismic features (spectral lines) that may be unique and potentially valuable to vehicle classification.

Signatures of Different Vehicles: The final investigation performed under the present phase was a comparison of the seismic signatures of four foreign vehicles during operation over flat ground and then over a bump. This study provided a snapshot of the differences between such vehicles, as projected by the upgraded model.

Sideviews of the modeled vehicles, which included the Russian-made BMP-2, MT-LB, T-72, and ZSU-23-4, are presented in the upper part of Figure 7. The lower part of the figure contains the spectrograms for each of these vehicles during operation over a bump. Similar simulations were made and results were produced for vehicle operation over flat ground. However, since most flat ground features can be seen in the early and late portions of the "bump" spectrograms (where there are no or minimal effects from the bump), no separate spectrograms are included for flat ground operation.

A direct comparison of the predicted spectrograms suggests that, under identical operating conditions, the seismic signature spectrograms of the four vehicles display distinctly different characteristics. Over flat ground (for example, prior to encounter with the bump), the number of tones (fundamental and harmonics associated with the track-shoe passage frequency), the relative intensity of these tones, and their directivity (tone variation with time or aspect angle) are some of the significantly different features of these vehicles.

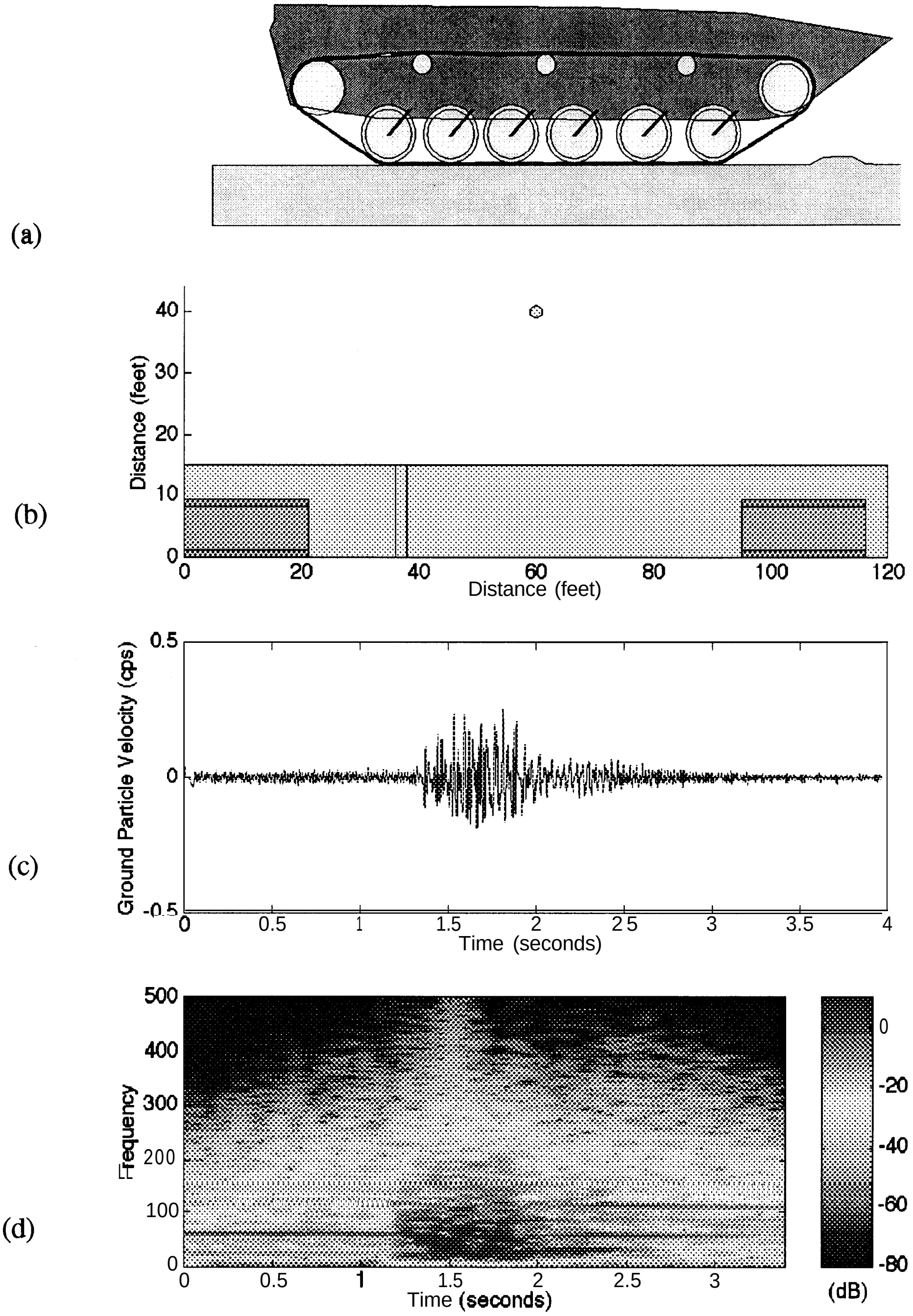


Figure 6. Predicted seismic signature for a BMP-2 operated over a bump. a) BMP-2 Approaching a Bump, b) Plan View of Vehicle Path, Bump and Sensor, c) Signature Time History, d) Signature Spectrogram

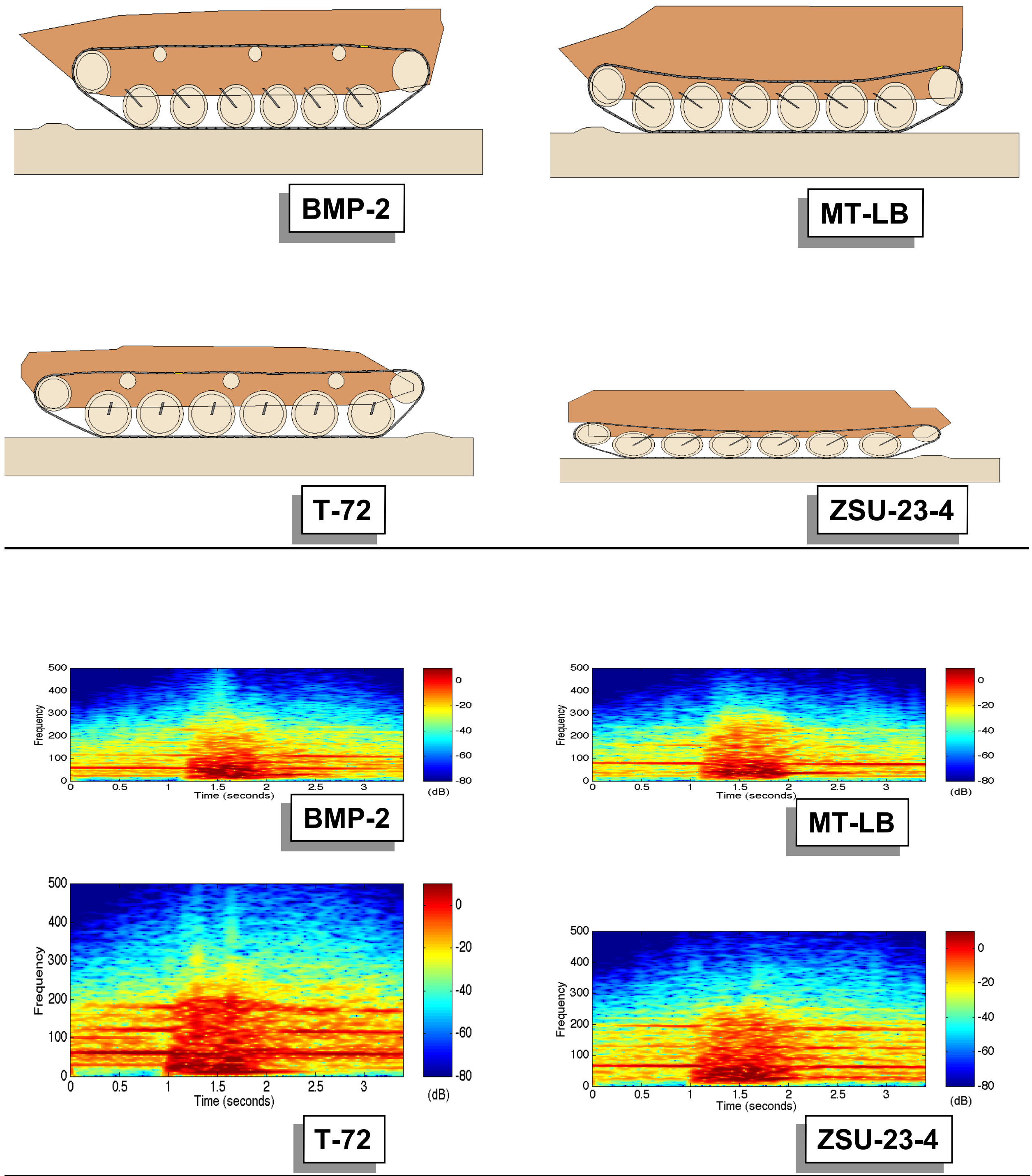


Figure 7. Comparison of Predicted Seismic Signatures of Four Foreign Vehicles Operated over a Bump.

The distinctions are further accentuated during an encounter with a bump. While the vehicle rides over the bump, the signature becomes intense but somewhat “nebulous” (with a significant broadband content) in a way that depends on the particular form of the bump. As the vehicle leaves the bump, the highly excited suspension relaxes predominantly through normal mode vibration. These modes introduce additional distinct tones in the downstream portion of the bump spectrogram. Such tones may offer additional information that may further facilitate vehicle classification.

It should be reiterated that the current model still involves some simplifying assumptions, including: vehicle model approximations, seismic wave propagation approximations, model parameter approximations; and absence of any background noise. Under actual conditions, these factors may obscure or may partially distort the specific form of the results. Accordingly, the predicted signatures and the current discussion should be considered preliminary, pending a rigorous model validation.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions: The results of the previous section are generally consistent with the basic conclusions of the earlier phase [1]. Specifically, the previously observed significant and potentially exploitable speed-dependent, seismic signature feature differences between various tracked vehicles have not been eliminated or diluted by the presence of newly introduced model features, such as the addition of a second track. These features include mainly the track-shoe passage frequency and its harmonics.

Furthermore, additional unique features, such as speed-independent normal mode tones, have been accentuated under certain conditions, such as during vehicle operation over a bump. Representative terrains (other than paved roads), used for movement of tracked vehicles, contain enough bumps to cause a continuous presence of these speed-independent tones in the vehicle signatures. Accordingly, these tones, that become more prominent over an uneven ground, further enhance the means of distinguishing the different tracked vehicles.

In the previous phase [1] the potential variation of the directivity pattern vs aspect angle was identified as a potential source of concern. Such variation is expected to complicate or prevent vehicle identification from a single spectrum, but it should not impede the process when a spectrogram is available. This expectation is supported by the distinct features of the Figure 7 spectrograms, but it needs to be confirmed through comparison to experimental results.

The most important conclusion that can be drawn from the predicted results of Figure 7 is that, under identical vehicle speed and soil conditions, the predicted seismic signature features of four representative foreign vehicles exhibit significant differences. If the prediction model is correct and these differences are real, (a matter for experimental confirmation), then these features should provide supplementary means for vehicle classification through existing technology.

Outstanding technical issues that affect the validity of the current predictions include: residual approximations in both the seismic force and wave propagation models; incomplete knowledge of soil parameters for any real test site; and, ambient noise due to meteorological, biological, or man made sources. The impact of these factors needs to be quantified through further investigations.

Recommendations: There are several areas in both the seismic force and seismic wave propagation models that can be improved by eliminating several of the current simplifying assumptions. However, before proceeding to additional levels of modeling sophistication, it is prudent to determine the validity range of the tools developed to date. Accordingly, it is recommended that near term efforts be focused in the following two areas:

- Parametric Studies: Both seismic force and seismic wave propagation models should be exercised for different vehicles, and a representative range of terrain, speeds, sensor distances, and background noise levels. The information should be used to develop further insight into vehicle behavior and the distinct features that may be used for vehicle classification.

- Model Validation through Field Tests: The parametric studies information should be used to design specific field tests for the purpose of model validation. Dynamic response quantities that can be conveniently measured, for direct comparison to their predicted counterparts, should be identified. Validation tests should be designed and conducted for both the seismic force and the wave propagation prediction models. For example, force model validation may be based on the comparison of predicted and measured acceleration of selected vehicle components. Subsequently, a validated vehicle model may be used to assess the validity of the current (Rayleigh wave) model for the description of the seismic wave propagation over representative types of terrain, sensor distances and frequency range of interest.

Specific areas requiring long term efforts will be determined from the findings of the near term tasks. Future work will probably require refinement of existing and/or development of additional model components and will likely focus in the following areas:

- Source Model: The source model may be improved, as needed, through additional features including, but not limited to, ground impedance, unconstrained (vertically and torsionally) vehicle hull, and improved parameter values for the all vehicle components (some are currently estimated).

- Propagation Model: The current soil model (semi-infinite, uniform elastic medium) used for the seismic wave propagation will augmented, as needed, through additional features including, but not limited to, other types of waves, soil stratification effects, and weather/seasonal variation of soil parameters.

- Sensor System: The current single sensor model will be replaced by a distributed sensor model to improve signal reception under realistic background noise scenarios.

- Full System Validation: Additional System validation tests will be conducted to determine the validity range of the entire model.

As designed, the recommended approach will focus future work on high payoff areas to improve the identification of seismic signature features that will facilitate vehicle classification, particularly when fused with information about other types of signatures. Concurrently, it will delineate the limitations of the developed tools in order to maximize their utility in practical applications.

REFERENCES

1) W. Coney and A. Galaitsis, "*Exploratory Predictions of Tracked Vehicle Seismic Signatures,*" 1998 Meeting of the IRIS Specialty Group on Acoustic and Seismic Sensing, Volume 1, Pages 97 thru 110, Paper B-1.
2) A. Galaitsis, *Countermeasures Signature Modeling*, BBN Report No. 7919, December 1993.
3) A. Galaitsis, "*Computer Simulation of Double-Pin Tracked Vehicles,*" TACOM Technical Report 13117, July 1995
4) A. Galaitsis, "Traxion: A Model for Predicting Dynamic Track Loads in Military Vehicles," in *Journal of Vibration, Stress and Reliability in Design*, Vol. 106, pp 286-291, ASME, April 1984.
5) P. Smith, "Formulas for Excitation and Measurement of Vibrations in an Elastic HalfSpace," in *Feasibility of Acoustic Landmine Detection Final Technical Report*, D. Sachs, *et. al.*, BBN TR 7677, May 1992.